The Catalina Sky Survey:
Challenges of Running a NEA Survey

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Elements of a NEO survey

- Equipment
- Software
- Survey Strategy
- People

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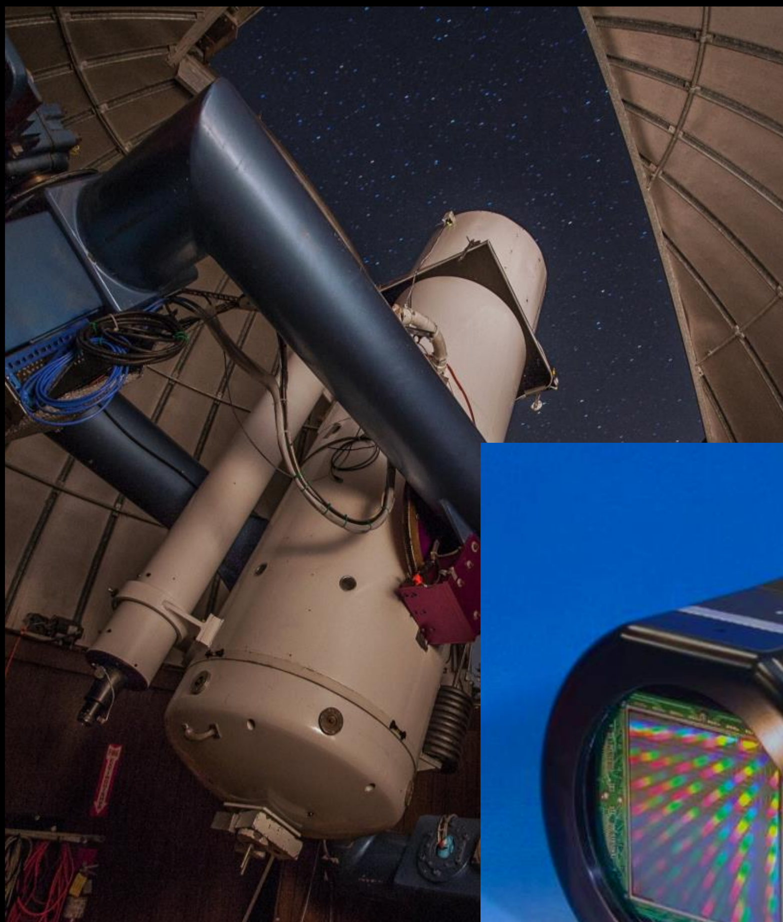
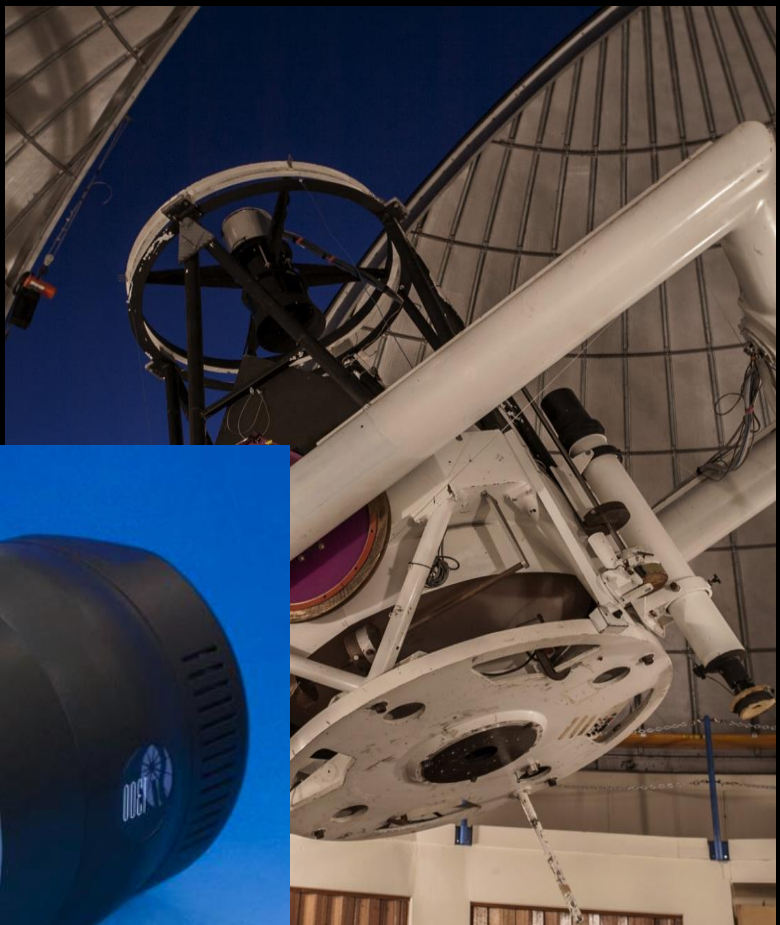
- People
  - Engineers, developers, observers

Equipment





Equipment

- Most NEO survey work is done by 1-m to 2-m class wide-field telescopes
- ALL current and past NEO survey telescopes were initially designed to do something else, or have competing science goals that can compromise the effectiveness of the NEO survey
- NEO survey efficiency benefits if everything can be optimized toward the single goal of discovery

Equipment

- Telescope
  - Primary metric is aperture, but optical design, f/ratio also matter
- Camera
  - Primary metric is FOV, but pixel scale, fill factor, readout speed, read noise also matter
- Computers
  - Telescope control, camera control, data processing – all need to be smoothly integrated

Equipment

- Survey power: *étendue*

$$A\Omega = Area * FOV$$

Area = collecting area, in m^2

FOV = Field of view, in deg^2

Equipment

- Survey power: [illegible]*ndue*

$$A\Omega = A[illegible] * FOV$$

Area = collecti[illegible] area, in [illegible]

FOV = Field [illegible] view, in deg[illegible]

Equipment

- Survey power: *modified étendue*

$$ME = Area * FOV * FF * T * OS$$

Area = collecting area, in m^2
FOV = Field of view, in deg^2
FF = Fill Factor of the focal plane array
T = Optical throughput
OS = Open Shutter efficiency (data throughput)

Still doesn't account for survey strategy, cadence choices, limiting magnitude, NEO population characteristics....

Try to maximize all inputs to this equation!

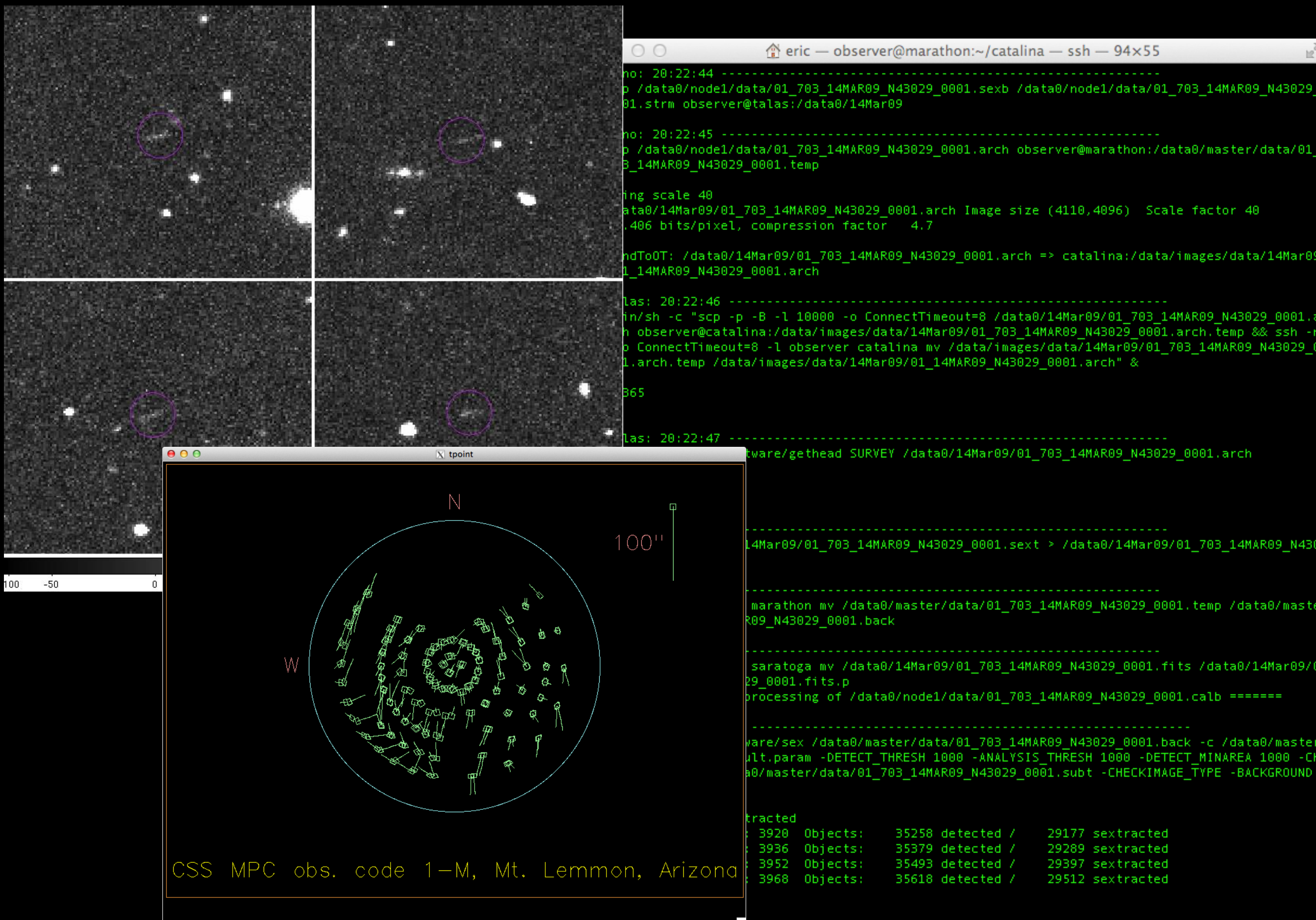
Equipment

- When adapting an existing telescope for survey use, modification of collecting area or FOV may be difficult or expensive
- Fill factor is especially important when multiple detections of an object are needed – baseline detection efficiency scales with FF to the n^{th} power, where n is the minimum number of visits for detection
- Example: 85% fill factor, 4 visits required for detection yields an efficiency of 0.85^4, or 52.2%

Equipment

- Throughput (optical throughput)
  - Can be estimated from number of mirrors, no. of transmissive optics, no. of AR coatings, CCD QE, filter characteristics
- Examples:
  - LSST 8.4-m : 3 mirrors, 3 correcting optics, 1 filter, 9 AR coatings = ~15% throughput
  - CSS 1.5-m : 1 mirror, 3 correcting optics, no filter, 7 AR coatings = ~75% throughput

Software



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Software

- Software is critical for any large-scale survey
- Data acquisition must be maximized (overheads minimized) – tight interfaces between telescope, camera + computers
- Large volumes of data must be processed quickly and reliably
- Must be maintainable and upgradable
- Steal what you can, write what you must

Software

- CSS has “stolen” general-purpose building blocks:
  - Source extraction software (SExtractor)
  - Image display software (SAO ds9)
  - Astrometry (imwcs, SCAMP)
  - Orbit calculation software (find_orb)
  - FITS manipulation routines (SAOTools)
- Don’t reinvent the wheel!

Software

- CSS has written NEO survey-specific elements:
  - Moving object detection software (con4)
  - Graphical user interface for acquisition and validation
  - Survey scheduling software
  - Image calibration software
  - Lots of scripting “glue” to stick the pieces together

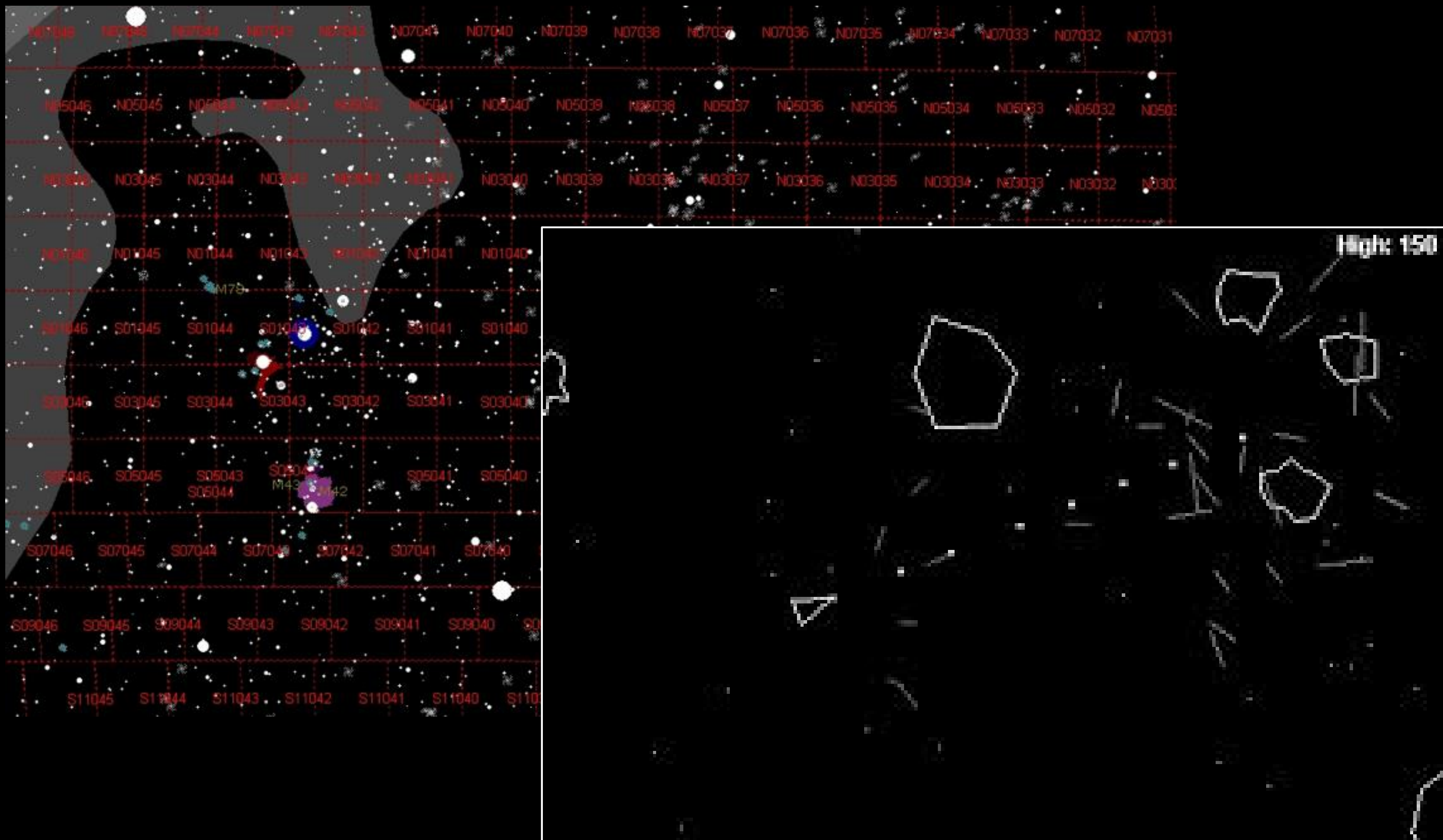
Software

- Acquisition pipeline:
  - For survey work, a tight integration between the TCS and camera is necessary
  - Main job is to sequence telescope, camera and shutter. Tasks must be interleaved to eliminate unnecessary overhead, e.g. telescope must slew while camera reads out
  - Other tasks may include calculating and applying focus adjustments, capturing telemetry to write to FITS header, fetching next coordinates, monitoring weather conditions
  - Minimize time not spent doing something critical. Fractions of a second per imaging cycle can matter!

Software

- Reduction pipeline
  - Involves familiar image reduction tasks (bias, flat, source extraction, astrometry, photometric calibration)
  - Must run quickly and reliably without human intervention, due to large data volume
  - Moving object detection software, e.g. MOPS, con4
  - Remember NEO discovery is the goal: can accept some amount of imperfect calibration as long as primary goal is met (NEOs are detected)

Survey Strategy

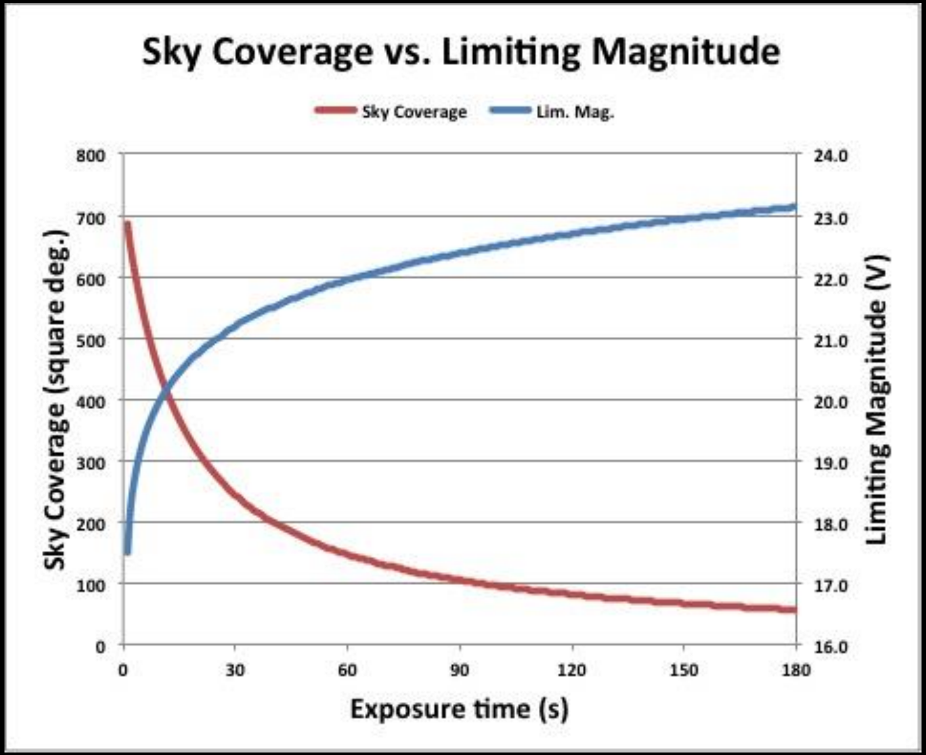


Survey Strategy

- So you have your survey system…what are you going to do with it?
- What are the characteristics of the NEO population you're interested in? Projection on sky, magnitude distribution, rates, known vs. unknown
- What are the strengths and weaknesses of other operational survey systems? Is there a niche to be filled? Where can you make the most impact?
- Considerations: exposure time, number of revisits, where to point (e.g. ecliptic, opposition, sweet spots)

Survey Strategy

- Coverage vs. Limiting Magnitude
  - Exposure time – how faint, when do trailing losses become a problem?
  - How many revisits for moving object detection?



Survey Strategy

- Real-time concerns
  - NEOs move quickly! Depending on rate, they must be followed up within 2 - 24 hours else positional uncertainties can become too large for efficient recovery
  - This drives pipelines and operational procedures toward real-time detection and reporting
  - Critical for unusual events, e.g. 2008 TC_3 and 2014 AA, ~3-m asteroids discovered <24 hours before impact
  - Everything begins with discovery: risk assessment, physical characterization opportunities, etc. Get a solid initial orbit as soon as possible

Survey Strategy

- CSS baseline survey strategies:
  - 0.7-m Schmidt w/ 8.2 deg^2 FOV, V_{lim}~19.7 : *all sky, bias toward ecliptic*
  - 1.5-m reflector w/ 1.2 deg^2 FOV, V_{lim}~21.3 : *+/- 5 deg. from ecliptic, bias toward opposition + sweet spots*
  - 0.5-m Schmidt w/ 4.0 deg^2 FOV in S. Hemisphere, V_{lim}~19.4 (now retired) : *all sky south of -30 Dec*

- 4 visits per night, total baseline 30-45 min.
- Revisit rates > 3-5 days

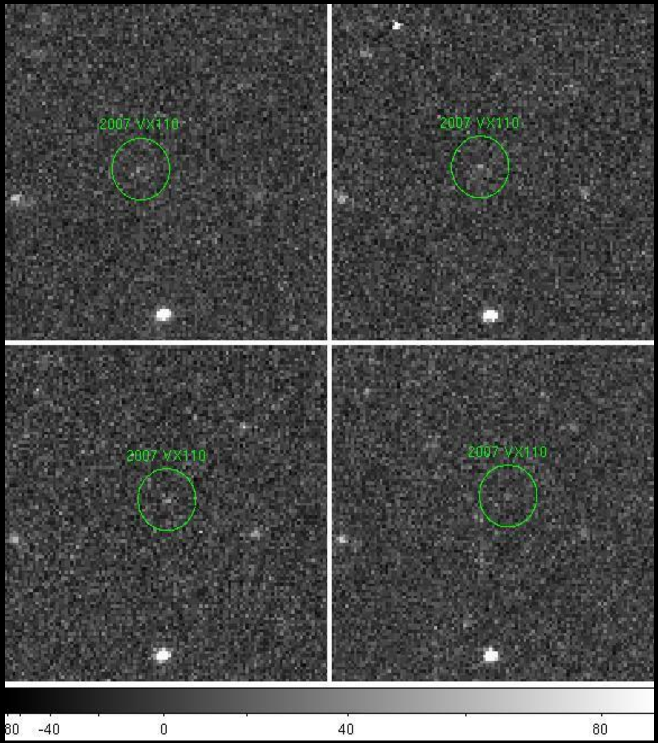
Survey Strategy

- Follow-up is an integral part of discovery
- Dedicated NEO follow-up capabilities exist. Typically new discoveries brighter than V~20 are followed up by amateur sites
- Fainter discoveries may need targeted follow-up, even if it means re-tasking your survey telescope to do the job

People

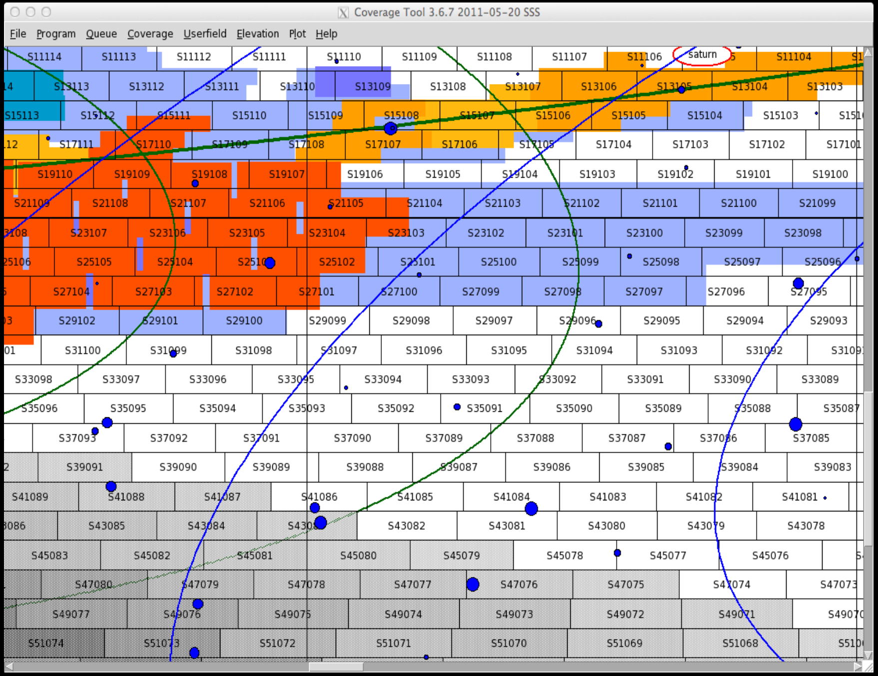
People

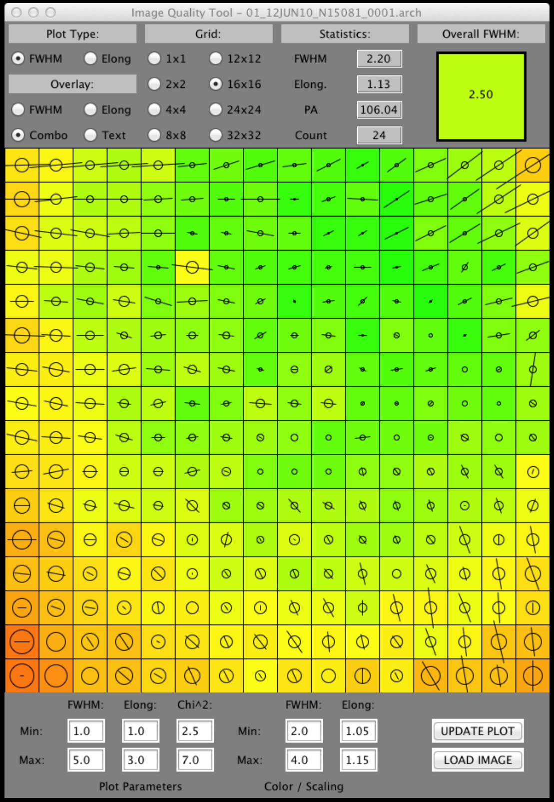
- Skilled observers can help *maximize sensitivity and efficiency* of the survey system
- At CSS, the fact that all NEO candidates are visually validated allows an extremely low detection threshold (S/N~1.2) and ensures a pure data stream



People

- Software for people vs. software for machines: people require specialized interfaces and visual feedback





People

- Challenges of incorporating people:
  - People may make different decisions at different times, and different people may make different decisions given the same inputs (non-repeatable)
  - People need to eat, sleep, socialize, get paid
- Don’t require people to do things that machines can do better (and vice versa)
- An ideal survey system fuses the best of human intelligence and adaptability, with the computational power of machines

Optimization

- Optimization is a constant task!
  - Telescope / camera system: maximize optical throughput. Collimation / image quality requires maintenance
  - Computing power increases with time – how can that work to your advantage?
  - Revisit fundamental assumptions often. Be prepared to modify survey cadence as our knowledge of the NEO population evolves, or as other survey assets evolve


GAME OVER
press ENTER to restart

Any further questions, please contact me!

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